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Investigating the impact of CAD simulations on student design thinking

Manaz R. Taleyarkhan
Purdue University

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Dr. Alejandra Magana
Chair

Dr. Senay Purzer

Dr. James Mohler

Dr. Carla Zoltowski

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INVESTIGATING THE IMPACT OF CAD SIMULATIONS ON STUDENT DESIGN THINKING

A Thesis

Submitted to the Faculty

of

Purdue University

by

Manaz R. Taleyarkhan

In Partial Fulfillment of the

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of

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For my parents.

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TABLE OF CONTENTS

Page

LIST OF TABLES

LIST OF FIGURES

ABBREVIATIONS

CAD	Computer Aided Design
GPA	Grade Point Average
MATLAB	Matrix Laboratory
SAT	Scholastic Aptitude Test

GLOSSARY

Computer Aided Design	A computer system used as a tool to create, simulate, and optimize a design to solve a given problem (Robertson & Radcliffe, 2009)
Informed Design	A system created by a designer whose level of competence lies between that of an expert and a novice designer (Crismond & Adams, 2012)

ABSTRACT

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Facilitating students to become “informed designers” is a goal in engineering education that has been proposed by multiple studies. The use of Computer-Aided Design (CAD) software has been used as a learning tool to promote design thinking in practical settings for undergraduate students. However, very little is known about the informed design process undertaken by these students while using the interactive and learning focused CAD tool to solve design challenges. This paper analyzes the nature of design thinking that happens when students use a particular CAD tool. In this study, I have adapted Crismond and Adams’ Informed Design Teaching and Learning Matrix (Crismond & Adams, 2012) to help identify qualities and patterns of informed design in the final artifacts of a class assignment using an educational CAD tool, Energy3D. It is hypothesized that a CAD software can help promote design thinking by allowing students to iterate and modify designs before submission thereby leading to increased informed design decisions and expert-like design practices. The major findings included that there was a significant increase between Reflection 1 and Reflection 2, in that there was evidence of more advanced design thinking evidence with students Understanding the design challenge and building knowledge. However, there was no significant change in students weighing options and making decisions or reflection practices.

CHAPTER 1. INTRODUCTION

1.1 Introduction

This chapter provides a broad overview of the research project and literature review of the subject matter. The introduction will review the scope, significance, definitions, assumptions, limitations, and delimitations of this research project.

1.2 Statement of Purpose

The use of Computer-Aided Design (CAD) software by designers and manufacturers goes back to the 1970s. These brought a revolutionary change in the engineering industry and brought the designers and engineers closer together, generating a need for a workforce skilled in both engineering and designing practices. While the demand for such skilled workforce was and still is high, there is still a dearth of such people in the industry. One of the primary reasons is the complexity of CAD software and the steep learning curve that discourages many engineers from adopting CAD software in their daily processes. Also, CAD models are often viewed as finished products that have to be presented as opposed to a learning and design tools that can be changed and tested (Roy & Group, 1993). These issues offset the benefits of using CAD software, particularly the advantage of being able to simulate, test, and design ideas quickly and in a cost effective manner. Thus, there is a need to address this challenge early on in the engineering college and help prepare a workforce of engineers that is comfortable working with CAD software and uses them as thinking tools while solving engineering challenges.

It is imperative that college students have experience with using CAD tools for solving authentic design challenges and developing design thinking. Such tools can scaffold the design thinking process and help them accomplish a task that is beyond their current abilities (Kern & Crippen, 2013). For example, a survey of CAD designers revealed that CAD tools support creative problem solving process by supporting enhanced visualization and communication, circumscribed thinking, premature design fixation and bounded ideation (Robertson & Radcliffe, 2009). However, the importance of developing such skills and the use of such tools in the classroom context is not widespread and often overlooked by educators (Weintrop et al., 2016). Moreover, evidence of effective teaching and learning techniques promoting design thinking and problem solving using such technology tools in schools has been scarce (Kim & Hannafin, 2011). While prior research suggests that first-year engineering students need to experience learner-centered, contextualized, fully interactive, multimedia learning environments (Rhoads & Hubele, 2000), very little is known about the informed design process undertaken by these students while using the interactive and learning focused CAD tool to solve design challenge.

Thus, this research aimed to integrate an easy-to-use CAD software in the freshman engineering class and inculcate a habit of using CAD software as thinking tools as well as resources for making design decisions in an informed way.

1.3 Scope

The scope of this research included understanding the design strategies that first year engineering students develop while using a particular CAD software as a resource for solving an engineering design challenge. This analysis focuses on finding whether the use of the CAD software aids the process of making informed design decisions and helps the students proceed towards developing expertise in the engineering design process. In this study, students use a CAD simulation software to complete a design challenge where they have to design an energy efficient home using solar energy. Students can design, construct, and simulate a green home iteratively over multiple cycles. Students actions included modifying the design parameters (e.g., size and type of roof, size and orientation of the walls, windows and solar panels, among others.) and observing the resultant effect on the energy consumption and cost of the house. Students have to make trade-off decisions between various design choices based on the feedback provided by the software. The final student generated models and post-test assessments in the form of reflection questions and summary questions developed by the course instructor will be used for probing into the students design process and their informed design decisions.

1.4 Research Questions

Two research questions guided this study. These questions were:

1. To what extent do students demonstrate evidence of design thinking in their reflections?
2. How does design thinking change after a hands-on iterative design learning experience?

1.5 Assumptions

This research study was based on the following assumptions:

- Students had a basic knowledge of computers and energy.

- All students took fundamental courses in math, science, and communication.
- All the students were familiar with project-based learning in which students are taught how to tackle open ended design problems that relate to real world engineering problems.

1.6 Limitations

This research study posed the following limitations:

- The study was limited to a participant pool drawn from the freshmen engineering design course offered by Purdue University. The participant pool may impact the ability of the study to be generalized.
- The study focused on participants who completed the segments of the study as outlined; final report, critical thinking journals, and scoring tool.
- Since students used the CAD software as part of the course, the instructor had full control over the way instruction is delivered and student interaction is managed.
- As part of the course, the instructor evaluated student-work and grades the deliverables.

1.7 Delimitations

The following delimitations were built-in to the design of this study:

- The study did not focus on any participant groups outside of ENGR 131.
- The study did not assess the usefulness of only one piece of CAD software.

- The study did not be assessing the qualities and benefits or disadvantages of the CAD simulation tool.

1.8 Summary

The purpose of this chapter was to provide a broad overview of the project, the gap filled with this study, and the general background of the subject matter. The introduction reviewed the scope, significance, definitions, assumptions, limitations, and delimitations of this research project.

CHAPTER 2. REVIEW OF RELEVANT LITERATURE

2.1 Introduction

This chapter provides a broad overview of previous research that has been done in this field. This chapter also discusses the current challenges faced in engineering.

2.2 Design Thinking and Engineering

Design thinking is a term first coined in a textbook in 1987 that revolves around an idea of a collective consciousness among design researchers (Rowe, 1991). The term has been explored for many years and eventually evolved into the paradigm describing a mindset for dealing with ill-defined problems (Dorst, 2011). Design thinking is essentially comprised of the processes of scoping a problem, generating possible solutions, evaluating the solutions, and realizing new ideas (Sheppard, 2003). This is done iteratively to optimize the solution to a design challenge and involves maximizing the "functionality of a design with respect to the design requirements and the resources available" (Silk & Schunn, 2008). While solving an engineering design challenge, students bring together an understanding of the available resources, consideration of the effect of multiple design parameters on the performance of the system, and understanding the trade-offs associated with various design decisions (Silk & Schunn, 2008). It is critical for engineers to think in terms of the complete system and at the same time understand how the individual parts function and together contribute to the functioning of the system as a whole (Silk & Schunn, 2008). Designing is a messy process with many possible solutions (Dankenbring, Capobianco, & Eichinger, 2014). Design thinking is very important to teach to todays students since there are many applicable real world situations in which this sort of thinking is required (Dorst, 2011) (Olson & Riordan, 2012) (Kober, 2015). Engineering design is a design process in which designer systematically break down a complex, ill-defined engineering problem in order to solve it. This process requires consideration of multiple variables at the same time, something that students have been found to be lacking in (Zohar, 1995).

2.3 Challenges Faced by Freshmen Engineering Students

A review of prior research highlights that it is critical to engage first year engineering students in a dynamic hands-on active learning experience in order to retain and help students learn disciplinary content (Prendergast & Etkina, 2014). A project based course designed for first year engineering students was found to increase the retention by 19% over a three-year period and also help improve the cumulative GPA by 3 tenths in addition to increasing the satisfaction of the students who took this course as compared to students following the traditional lecture mode of learning (Prendergast & Etkina, 2014). The importance of helping students learn systems thinking and engage with systems dynamics has been the focus of many previous research studies (Gharajedaghi & Ackoff, 1985; Sterman, 1994). However, a survey report found that freshmen involvement with projects was not found to be as effective as expected since students lacked the technical knowledge or tools to benefit fully from their experience (Christophersen, Coupe, Lenschow, & Townson, 1994).

An in-depth study comparing freshman and senior engineering students approaches to an open-ended design problem - designing a playground for a fictitious neighborhood - showed that the freshman considered fewer alternative solutions, implying fixation on a specific solution path. Furthermore, they did not proceed into the final steps of the design process as much as the seniors did (Atman, Chimka, Bursic, & Nachtmann, 1999). This highlights the need for significant scaffolding to help first year students engage with design thinking and learn the engineering design disciplinary practices. Educators have recommended the use of more hands-on teaching methods using graphics and simulations (Clough, 1997; Ramos & Yokomoto, 1999). Ramos and Yokomoto used MATLAB as part of course in probability in order to make it real and relevant to the electrical engineering students. They found that MATLAB helped students understand the disciplinary concepts as well as learn how to use them to solve real challenges (Ramos & Yokomoto, 1999). Along the same lines, Computer Aided Design (CAD) simulation tools have been increasingly gaining prominence in the engineering curricula.

2.4 CAD Simulations to Support Design Thinking

Computer Aided Design tools are used to create, model, analyze, or manipulate concepts in a computer system (Robertson & Radcliffe, 2009). CAD simulations provide a unique opportunity to design, build, and refine a possible solution to a given problem (Carberry & McKenna, 2014), and plays an important role in helping students learn design thinking (Brown, 2009). By providing feedback to the users highlighting the cause-effect relationship between the design parameters and the outcome parameters, these tools aid in the process of scoping the problem, generating possible solutions, evaluating the solutions, and realizing new ideas. CAD tools support the engineering design process by enhancing visualization, prototyping, testing and communication of ideas, and modeling activities (Carberry & McKenna, 2014; Dym, Little, Orwin, & Spjut, 2004; Robertson & Radcliffe, 2009). Moreover, CAD tools enhance understanding of the problem and design process (Carberry & McKenna, 2014), and increase efficiency and efficacy in creativity (Xie, 2014b). Perhaps the most important affordance of CAD tools is the ability to visualize ideas. This allows students to externalize their ideas and design concrete representations of abstract ideas that aids in effective communication of design ideas (Robertson and Radcliffe, 2009). While the expectation is not that the first year engineering students will become experts as a result of such scaffolding, researchers suggest that there is an important intermediate step of becoming informed designers that can be achieved via such scaffolding (Dreyfus & Dreyfus, 2005) (Crismond & Adams, 2012). "Compared to experts, informed designers pattern-matching skills would be less reliable, and their retrieval and use of learned ideas would be done less flexibly, since those ideas would have fewer connections to other thoughts" (Crismond & Adams, 2012).

2.5 Chapter Summary

The purpose of this literature review is to situate this research study within existing literature and highlighting prior work that has been done in this area. This chapter also discusses the context and current challenges faced in engineering.

CHAPTER 3. CONCEPTUAL FRAMEWORK

3.1 Introduction

This purpose of this chapter is to discuss the framework that scaffolded this study. There are also descriptions and examples of how the framework is applied.

3.2 Informed Design Teaching and Learning Matrix

Informed design is a stage of design thinking that lies between the stage of a novice designer and an expert designer. Informed design engages the students in a way that enhances their own related skills and knowledge before coming up with new designs to solve the specifications of the problems context. The learners can build upon their prior knowledge in order to reach a new solution, as opposed to a novice designer who relies solely on trial and error. Trial and error problem solving does not guarantee conceptual closure (Crismond & Adams, 2012). The informed design approach requires a preexisting knowledge of the related math and science concepts that relate to the context of the design problem. This prior knowledge improves design performance and prompts inquiry learning. The Informed Design Teaching and Learning Matrix from Crismond & Adams will help provide a framework to identify patterns in the student artifacts that can help us determine if informed design is being displayed. Table 3.1 summarizes key patterns in identifying design habits and distinguishing those that are prevalent in beginner vs informed designers (Crismond & Adams, 2012). For example, if a student discusses weighing one design decision over the other based upon perceived benefits and constraints, then the student is displaying a trait of an informed designer. Beginning designers on the other hand tend to ignore these types of comparisons and often jump ahead with decisions without weighing consequences ahead of time. While the Crismond and Adams matrix encompasses various design strategies, I will use a subset of these strategies that are meaningful in the context of this research and data available for analysis. These strategies will help me identify traits that show whether the students are developing a mindset that is expected from informed designers. Table 3.1 summarizes the complete matrix and highlights the strategies that are not being considered for this study.

3.3 Understanding the Challenge: Problem Solving vs. Problem Framing

Beginner designers look at a problem and feel that the setup and answer are very straightforward. This usually sets up the whole design process to be very linear because the initial understanding of the context is simplified. Beginner designers usually see the problem and dive right in without fully understanding any hidden complexities or nuances in different solutions or problem solving methods. Informed designers tend to read the problem and then wait before attempting to solve it. A more robust design can emerge by delaying design decisions and prototyping and instead framing the problem in a more detailed context.

3.4 Build Knowledge: Skipping vs. Doing Research

Beginner designers tend to go the quickest route to solve a problem and move on, and this usually means they neglect to do any research. An open ended design challenge can be extremely daunting to a student, especially given that their

Table 3.1: Summarized Informed Design Teaching and Learning Matrix (Crismond & Adams, 2012)

Design Strategies	Beginner	Informed
Understand the Challenge	Prematurely attempt to solve without identifying key components in problem structure.	Identified critical criteria and constraints as well as the ultimate goal of the design task.
Build Knowledge	Skip all research and begin solving.	Investigate and learn more about the problem context before coming up with solutions.
Generate Ideas*	Work with one or a few ideas and remain fixated.	Create as many ideas as possible, brainstorming.
Represent Ideas*	Propose ideas that would not work if built.	Multiple representations to investigate and explore design ideas.
Weigh Options and Make Decisions	Criteria and constraints are not considered for decision making.	Use the trade-offs and potential benefits as the main input parameters of the decision making process.
Conduct Experiments*	Conduct very limited experimentation when they do.	Identify and conduct valid tests to assess the appropriateness of the proposed solution.
Troubleshoot	Unable to think critically and troubleshoot their proposed solutions.	Focus on specific problematic areas and propose strategies to approach them.
Revise/ Iterate*	Work in linear order without considering iteration	Iterate using the feedback from conducted experiments to refine their solution.
Reflect on Process	Conduct little or no reflection and monitoring activities to their plans or proposed solutions.	Conduct informed reflections based on previous experiences and iterations.

entire academic career has been set on cut and dry problem and solutions with little to no prior research required. Similar to Pattern A. Problem Framing, informed designers realize that a delay in design decisions in order to do research on the background of the problem can lead to a better solution than if no research was conducted. Informed designers take the time to learn more about the problem context such as the end users of the product or tool or past results from other attempts to solve the problem.

3.5 Generate Ideas: Idea Scarcity vs. Idea Fluency

A beginner designer will often proceed forth after examining a few possible ideas and then move forward in the process. Once again, an informed designer will delay in prototyping or acting upon a design decision until more groundwork is laid, meaning an informed designer will have a lot of ideas before proceeding forward. Some of the reasons for this is that beginner designers are easily fixated on an idea since throughout their academic careers, students are usually not rewarded for coming up with a new way to solve a problem in the classroom. This is unfortunate since coming up with many ideas can save time and resources. Beginner designers often fixate on an idea because they have spent so much time developing it, whereas an informed designer examines a wide range of ideas before honing in on one or two viable options to develop.

3.6 Represent Ideas: Surface vs. Deep Drawing and Modeling

Beginner designers do not consider constraints and drawbacks when producing and sketching potential ideas for a design solution. In fact, beginner designers may not produce sketches at all, let alone viable ones. Informed designers are able to generate feasible ideas that have a possibility of being created because they are able to construct these possibilities while keeping in mind device knowledge and scientific properties that could influence appearance or structure of model generated.

3.7 Weigh Options & Make Decisions: Ignore vs. Balance Benefits and Trade-offs

Beginner designers may only describe the reasoning behind their design choices by mentioning how their design has good qualities while rarely mentioning what they had to give up for that choice. On the flip side of the coin, beginner designers will highlight the drawbacks of a rejected approach and neglect to mention any possible benefits of that decision. Informed designers are very aware and very descriptive of what they had to give up in order go forth with a design choice. Being aware of the consequences of different design choices (and being able to articulate them) can lead to more fruitful iterations of prototypes or models and eventually lead to more optimal final designs.

3.8 Conduct Experiments: Confounded vs. Valid Tests and Experiments

Informed designers often test and iterate their designs throughout the design process. Beginner designers rarely test and iterate their final products, and when they do they do not effectively test. This yields little to no valuable information gained from testing. Professional designers, or experts, realize the value of generating insights in an efficient manner. Informed designers are realizing the benefits of having systematic and valid tests as a way to learn about their design decisions and how different variables can be altered to achieve the desired outcome.

3.9 Troubleshoot: Unfocused vs. Diagnostic Troubleshooting

Beginner designers tend to overlook or misdiagnose any problems in designs. Informed designers will hone in on problematic areas and work towards solving the problems. What a beginner designer sees as satisfactory an informed designer will view as a “flawed design.”

3.10 Revise/Iterate: Haphazard or Linear vs. Managed and Iterative Designing

Beginner designers tend to work haphazardly redirecting to whatever problems emerge and their design stages are extremely liner. Informed designers iterate their design process in a systematic fashion.

3.11 Reflect on Process: Tacit vs. Reflective Design Thinking

Beginner designers rarely think critically about their design if at all. Informed designers will look back on previous work throughout the design process and systematically consider improvements based upon new information or constructive feedback.

3.12 Chapter Summary

The purpose of this chapter was to discuss the conceptual framework vital to the structure of this particular project. This chapter also described and gave examples of how the framework was applied.

CHAPTER 4. METHODOLOGY

4.1 Introduction

The purpose of this chapter was to understand patterns in student design thinking when they solve an engineering design challenge using a CAD simulation tool, and determine whether the simulation tool can scaffold patterns associated with being informed designers. This chapter presents details about the research design, data collection method, participants, context, and data analysis technique. This research study focuses on understanding first year engineering students design practices while using a CAD simulation software and aim to identify evidences of skills that are expected of informed designers. This research study uses a type of CAD software called Energy3D that allows students to design an energy efficient house. Energy3D is free, open-source software that allows students to create 3D buildings and simulate energy consumption (Xie, 2016a). Students use this tool to construct and simulate energy usage in a home while working within a given set of constraints (e.g., fixed budget).

4.2 Research Design and Data Collection

In this research, I will focus on first year engineering students in a freshmen engineering design course and will use student artifacts for analysis. Thus, the dataset for this research consists of two sets of data that were obtained from the two instructors teaching the same learning module to different First Year Engineering classes.The students used Energy3D as the primary CAD software for solving the design challenge. I used a sample of students from one instructors section to refine my coding scheme. I used a sample from a second instructors section to implement and analyze the student artifacts to answer my research questions. The structure of the learning module followed by the instructors was similar, but there would definitely be instructor-specific differences that may influence the outcome of this analysis. While I acknowledge that such differences may exist and influence the student artifacts, it is beyond the scope of this research. The table below provided by one of the course instructors describes the process the students went through to produce the artifacts that this thesis will examine. It must be noted that for the first section, I only analyzed the final reflections since initial reflections (reflection #1) was not available for analysis. I used these final reflections to develop my codes. I refined and applied these codes to the final reflections for both the sections. In addition, I compared reflection #1 and #2 from the second section using the codes to get a more nuanced understanding of the effect that the Energy3D software might have had on students design thinking.

Students started by learning how to use the Energy3D software and explored the affordances of the software individually. They then applied the material taught in lecture regarding design cycles and weighted decision making towards their interaction with the Energy3D simulation tool for solving the design challenge. They applied any new knowledge towards improving their designs and then presented their design in front of their peers during a class presentation. All students filled out reflection questions that probed them to understand their thinking process. Instructors for the freshmen engineering design course were contacted for this IRB approved study to provide data. The first data set was provided by Instructor 1 and

Table 4.1: Lesson Plan for Freshmen Engineering Design Course

Design Class	Topics and Tasks	Deliverables
Class 1	Learn to use software and create an individual solution	Individual solution and Reflection 1
Class 2	Connect to the design cycle and work in groups to create a team solution	None
Class 3	Learn about weighted decision matrices and continue group work	None
Class 4	Finalize and present team solution	Team Solution and Reflection 2

included: Reflection #2 from Day 4. The second data set was provided by Instructor 2 and included: Reflection #1 from Day 1 and Reflection #2 from Day 4.

4.3 Participants and Context

The context of this study is a freshmen engineering design course consisting of students interested in pursuing an engineering discipline. There are no college prerequisites indicating prior knowledge for the entering freshmen students. However, a basic understanding of math concepts is assumed because a requirement to enter the Purdue undergraduate engineering program is a benchmark score on the well-known Scholastic Aptitude Test (SAT) which currently includes arithmetic, algebra, geometry, and data analysis. The student only needs to have a brief overview of the concept of solar energy and a demonstration of the Energy 3D software, both of which the instructors are required to provide prior to the students interacting with the simulation tool. The population of the first section of students consisted of 120 students, from that I randomly selected 7 final reflections for developing and refining the coding scheme. After refining my coding scheme 7 times, I moved on to the second section. The second section consisted of 120 students. Of those 120 students, 90 had both Reflection 1 and Reflection 2 artifacts. I implemented my coding scheme on those 90 students Reflection 1 and Reflection 2 responses.

4.4 Materials

Energy3D is a computer-aided design software with solar energy simulation capabilities. All students used the Energy3D simulation software to design an energy efficient house. Students were expected to evaluate possible constraints and possible options and determine the best possible options for designing an energy efficient home. The software allowed users to design and test possible designs and enabled them to perform iterations on previous designs based upon the simulations outcomes. Figures Figure 4.1, Figure 4.2, and Figure 4.3 show the Energy3D user interface. Students are given a design challenge in which there is freedom for them to choose the dimensions, materials, as well as the size and number of windows and solar panels. As shown in Figure 4.4 and Figure 4.5 there are constraints to constructing their home such as the final size and cost. Their final submissions are artifacts that describe their design decisions given the design constraints. Please refer to the Appendix A for further information on Energy3D reference tools that were provided to the students.

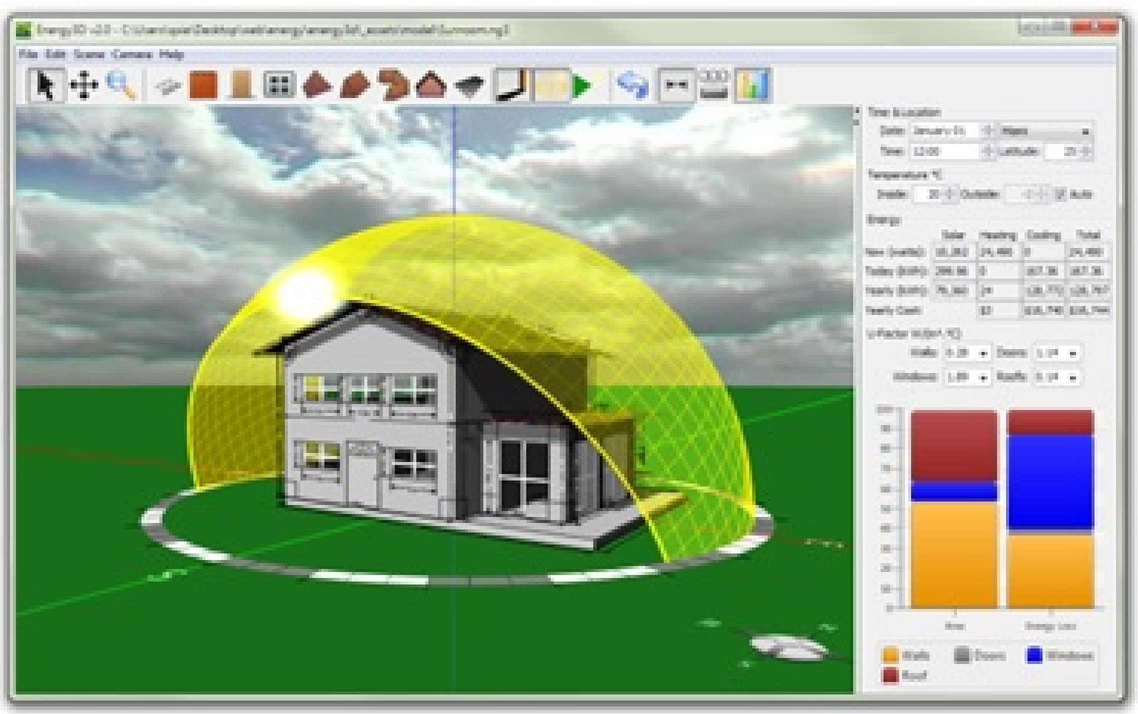


Figure 4.1.: Energy3D User Interface

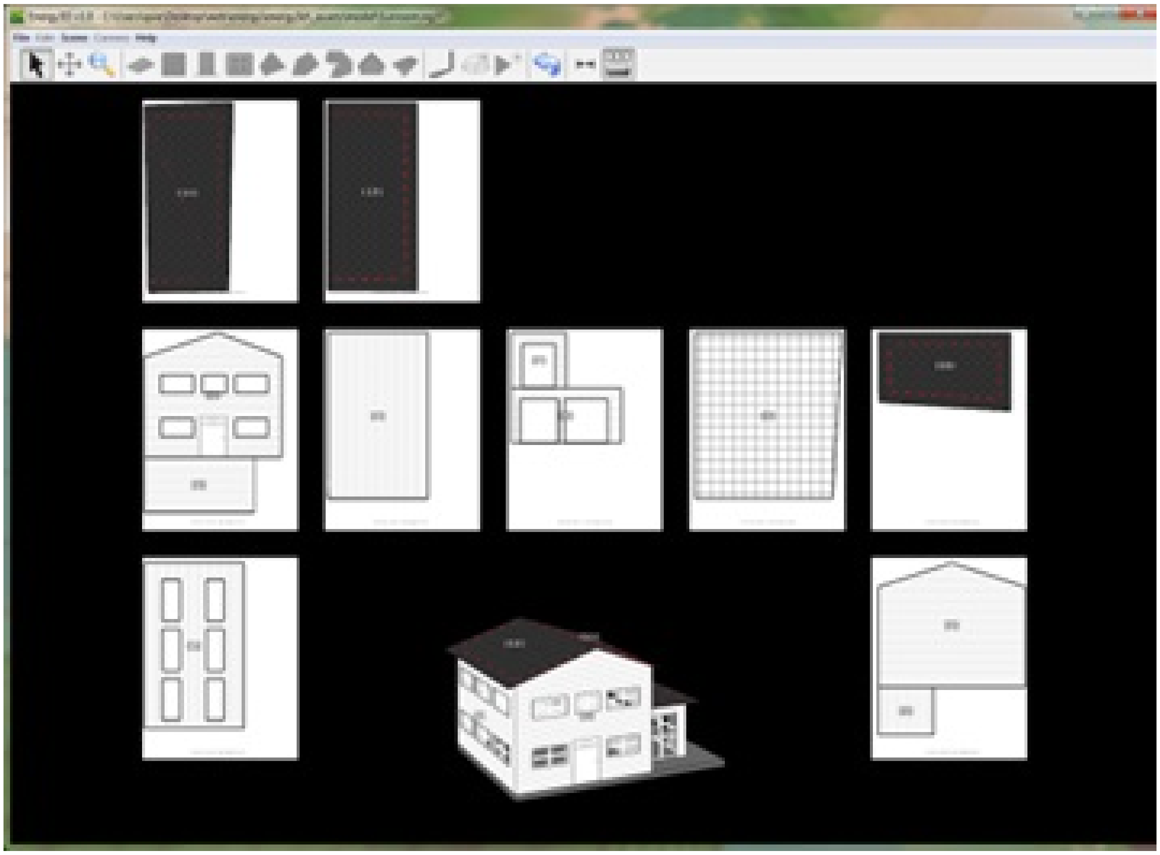


Figure 4.2.: Energy3D Home Components

More specifically, the students were given a background on the problem context, in this case the background states:

> The client, a promising mid-size company, is committed to becoming a leader in the area of passive solar energy in residential buildings. According to the client, “All newly constructed buildings must consume nearly zero energy by the end of 2020.” The key to solving this challenge is finding a way to take advantage of the free and unlimited energy from the sun without compromising the thermal comfort of the buildings for the occupants.

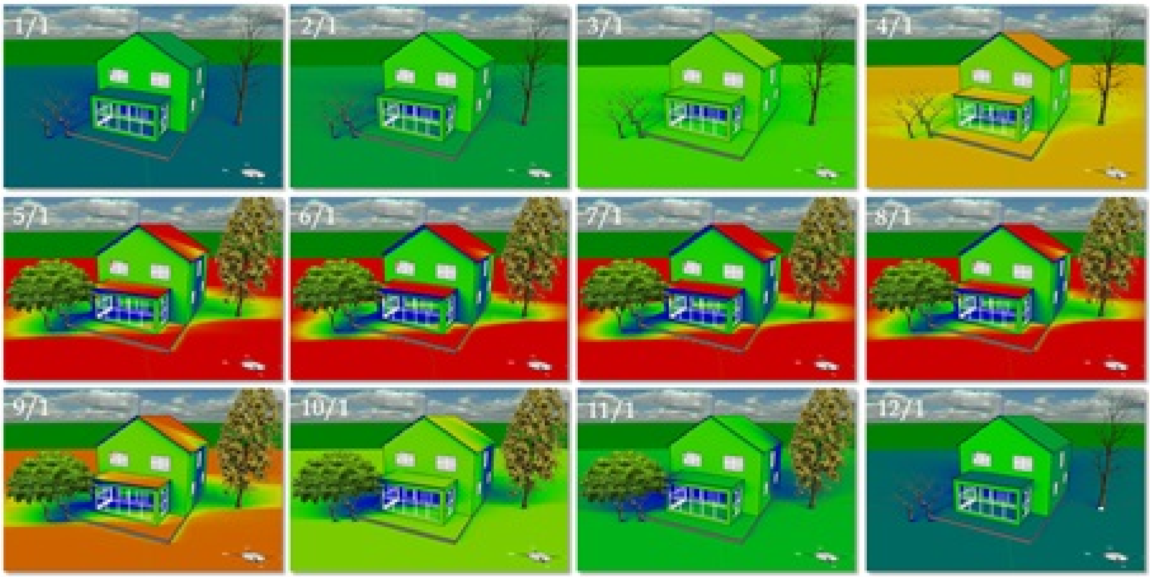


Figure 4.3.: Example of Energy 3D Simulation

The students are given a design challenge that requires a zero-energy residential building, with the requirements that they use the Energy3D platform.

The grading criteria are paraphrased below:

- Net energy that the building annually generates and uses should be zero or less.
- The material cost of the structure should be minimized.
- Simple design, the building should be easy to construct.
- The building needs to be aesthetically pleasing.
- The building should be able to house a family of four with a building area of about 100-200m2 and 6-10m in height. (Default size being 12m-16m)

The constraints are paraphrased below:

Design a Zero-Energy Building

Background
The client, a promising mid-size company, is committed to becoming a leader in the area of passive solar energy in residential buildings. According to the client, "all newly constructed buildings must consume nearly zero energy by the end of 2020." The key to solving this challenge is finding a way to take advantage of the free and unlimited energy from the sun without compromising the thermal comfort of the buildings for the occupants.

Design Challenge
The client has submitted a request for proposals for a **zero-energy residential building**. They are looking for a design that consumes no net energy over a year.

Statement of Work
The client wants all energy-cost simulations to be performed using the Energy3D platform. This software is available for download at http://energy.concord.org/energy3d.

Criteria

A successful design must meet the following criteria:

- The total amount of energy that the building uses annually should be equal to or less than the total amount of renewable energy that it generates.
- Minimize total cost of the building (material cost)
- Should be easy to construct
- Should have an attractive exterior or "curb appeal"
- Comfortably fit a 4-person family (approximate building area 100-200 m^2 and height 6-10 meters) (default platform size is 12m x 16m)

Constraints
In addition there are geometric and budget limitations:

- The cost of building materials cannot exceed $50,000
- Each side of the house must have at least one window on each floor.
- Tree trunks must be at least two meters away from the house.
- Solar panels cannot hang over roof edges.
- Roof overhang must be less than 50 centimeters wide (the default is 25 cm).
- A house is defined as a space enclosed by one and only one set of connected walls. Don't put multiple houses on the platform. Do not add entry porches, dormers, chimneys, garages, or driveways. Do not add additional buildings such as guest houses, dog houses, etc. **You can only build one house on the platform.**

Always document your work, especially your analyses about the energy performance, in the Note Area. Your notes will be automatically saved when you save your design.

Note: *Design challenge associated with NSF DUE # 1348547 & 1348530. Purzer (PI) & Adams (co-PI)* 1

Figure 4.4.: Design Challenge

ENGR 131 PROCESS

You will spend four class periods carefully planning, constructing, experimenting, analyzing, optimizing, and documenting your designs. You will develop a preliminary design developed individually and a final design developed in a team.

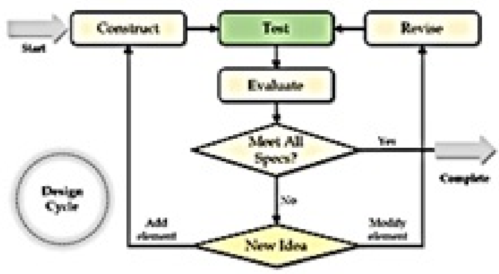
The Design Deliverables and the Statement of Work

- Preliminary design (competed individually, *see Design Specs Sheet*)
- Reflective design
- Final design (*see Design Specs Sheet*)
- Reflective design

Suggested Engineering Design Cycle Using Energy3D

At the beginning, you should explore a variety of design alternatives. Remember to compare the cost and energy performance data frequently. Energy3D can automatically calculate the annual energy usage for heating and cooling. Based on your evaluation of the results, you will decide how to improve the energy efficiency of the house. Meanwhile, your design must meet all the other specifications from the client.

There are a number of different design cycles you can use. Here is an example:



Evaluation of Design Process (30 points)

	WOW, this is expert-like behavior! ← 30 pts	0 pts → No evidence of informed design behavior
Problem Scoping	*Asked questions, conducted investigations, interviews, observations and explored the real challenges early in the process and iterated when necessary*	*Did not engage in a deeper exploration of the problem*
Idea Generation	*Generated a large number of ideas. Used a variety of idea generations methods. Used multiple representations, built quick/simple prototypes to test ideas.*	*Fixated on a single idea*
Experimentation	*Gathered information, conducted experiments to evaluate alternative design solutions. Used graphics or other data to compare benefits and trade-offs of ideas.*	*Decisions are made in a haphazard way based on assumptions and no experimentation or information gathering*

Evaluation of How the FINAL Solution Meets Design Criteria (20 points)

Does the final solution meet the following criteria and constraints?

- ☐ There is only one house on the platform. (All calculations would be inaccurate if you have not met this constraint)
- ☐ The total amount of energy that the building uses annually should be equal to or less than the total amount of renewable energy that it generates. (x5)
- ☐ Total cost of the building is minimized and does not exceed $50,000 in material cost (x5)
- ☐ Comfortably fit a 4-person family (approximate building area 100-200 m^2 and height 6-10 meters) (x2)
- ☐ Should be easy to construct (x2)
- ☐ Should have an attractive exterior or "curb appeal" (x2)
- ☐ Each side of the house must have at least one window on each floor.
- ☐ Tree trunks must be at least two meters away from the house.
- ☐ Solar panels cannot hang over roof edges.

Note: Design challenge associated with NSF DUE # 1348547 & 1348530. Purzer (PI) & Adams (co-PI) 2

Figure 4.5.: Example of Energy 3D Simulation(continued)

- Building material costs must be less than $50,000 USD.
- One window per side per floor.
- Trunks of trees must be at minimum 2 meters away from the home.
- Solar panels must not exceed or hang over roof edges.
- Roof overhang cannot be more than 50 cm, the default being 25cm.
- For the purposes of this assignment, a house is one set of connected walls surrounding a single enclosed space. Additions such as garages, driveways, dog houses, chimneys, etc. are prohibited.

Students are encouraged to document their work in the designated "Note Area" of the Energy3D software, as well as use an iterative design cycle over the course of four class periods. Figure 4.6 is a figure from the assignment handout that depicts the suggested design cycle for this particular project (Xie, 2016b).

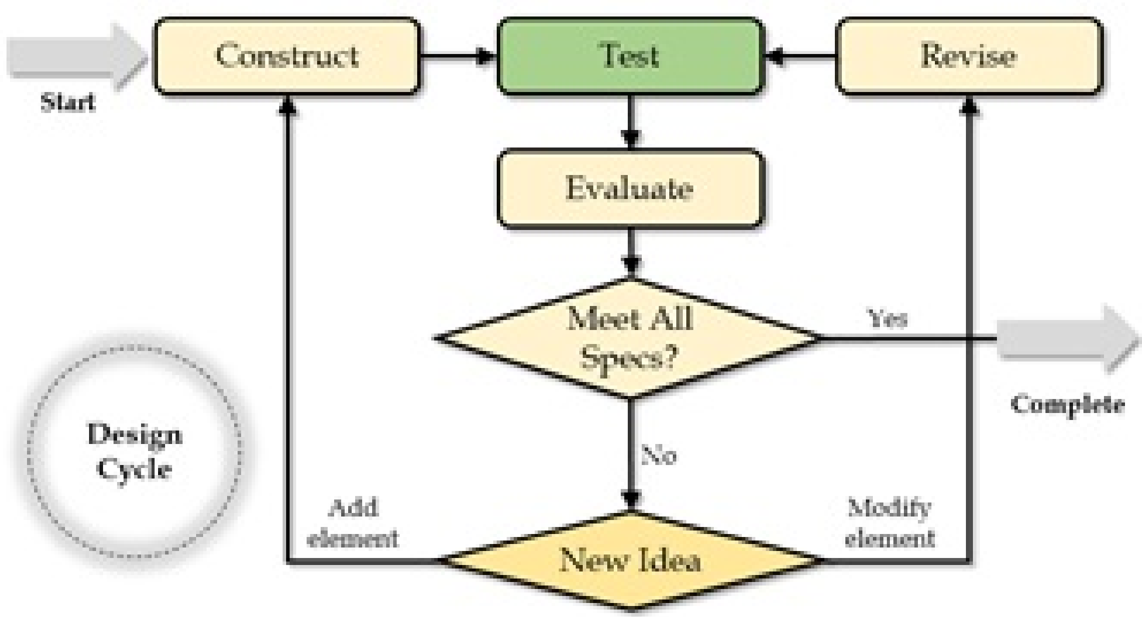


Figure 4.6.: Recommended Design Cycle (Xie, 2016b)

4.5 Data Analysis

The initial data obtained from the first instructor is referred to as section 1 for this research project. For section 1, I analyzed the data using content analysis. I coded the student reflections and reduced them to specific categories informed by Adams and Crismonds framework. I identified themes highlighted by the coded categories and their occurrences in my dataset. I identified patterns in the reflection responses from all the students and used them to inform the development of a set of codes that helped me analyze whether characteristics of informed design were visible in the responses. The codes were based on the adapted Informed Design Teaching and Learning Matrix. I started with a subset of students from section 1 and used the responses to refine my codes to make them relevant in this researchs context. I obtained data from another instructor that included both reflection 1 and reflection 2 for each student. Then I applied these codes to the entire relevant dataset of section 2nd identified patterns and themes in the data to answer my research questions. Another researcher reviewed the codes and applied them to a subset of the dataset (7 students). The codes and coded student-responses were then discussed in a one-on-one meeting with the researcher to ensure the codes conveyed a consistent meaning. If any differences were noted then we discussed the rationale and refined the codes to accurately align them with the data, framework and research questions. The refined codes were then used to code the entire dataset of the second dataset of 90 students. The non-parametric Wilcoxon Signed Rank test was used to determine if there was a significant difference in the evidence of more proficient design thinking in Reflection 2. The design strategies are nominal variables, and the patterns were ranked as a measurable variable. Values given were as follows: beginner = 1, adept beginner = 2, informed= 3, adept informed = 4. Reflection 2 results are not independent of Reflection 1 results, also the data distribution cannot be assumed to be normal, and there are multiple categories being compared.

4.6 Section 1 Data Coding Scheme

Here, I outlined a sample coding scheme that I generated after analyzing seven students from the first section. Please refer to Appendix B for results of this preliminary analysis. The categories highlight various design strategies representative of informed designers and draw heavily from the Informed Design Teaching and Learning Matrix. I have provided sample student responses from my data subset for each category. It should be noted that not all the categories are represented in the section 1 data set. An example of evidence of design is referred to as "Example." If no example was found in the data set, then I refer to a "Hypothetical counter example."

4.6.1 Understanding Design Challenge Problem Solving vs. Problem Framing

Beginners assume that the design problem is well defined and straightforward, so they make attempts to solve it without trying to comprehend the problem better by exploring and framing like informed designers do.

- Example of beginning designer: "I tried to minimize the amount of energy used by the four windows that were required in the specifications of the customer." In the example, the student reduces the design task to a straightforward problem of minimizing the energy consumption by the four windows.
- Hypothetical counter-example of informed designer: "I read about the problem, and looked at all the features and constraints of the software and tried to understand the end goal better." In the example, the student took time to address and understand the problem before starting the process of problem solving.

4.6.2 Building Knowledge Skipping vs. Doing Research

Beginners skip doing research and go straight to building solutions unlike informed designers who do research and investigate using the given resources.

- Hypothetical counter-example of beginner designer: "We read the problem and started making a house." In the example, the student did not conduct any research and went straight to solving attempts.
- Example of informed designer: "I read the Energy3D user manual and they commented about the uses of trees in the program, so I applied it to my houses situation as well." In the example, the student performed a little investigation and uses the Energy3D manual to build knowledge about the usefulness of trees in reducing energy usage.

4.6.3 Generate Ideas Idea Scarcity vs. Idea Fluency

Beginners become fixated on an idea and refrain from exploring alternative ideas like informed designers do.

- Hypothetical counter-example of an informed designer would be, “We brainstormed many ideas and talked about them before settling.” In the example, the students were flexible about generating many ideas and jumping from one to the other before honing in on one.
- Hypothetical counter-example of a beginner designer would be, “We thought of one idea and went for it.” In the example, the students fixated on a single idea.

4.6.4 Weigh Options & Make Decisions Ignore vs. Balance Benefits & Trade-offs

Beginners make design decisions without weighing various options and ignore trade-offs unlike informed designers who weigh the benefits and trade-offs before finalizing a design.

- Example of beginning designer: “I decided to use the best materials for the walls to help insulate the building.” In the example, the student focused on just the quality of the insulation ignoring the cost associated with using the best material. While using the best material would be desirable from an energy reduction perspective, it will increase the cost of the house and is less desirable from a budget perspective.

- Example of an informed designer, “I placed deciduous trees in such a way that they blocked sunlight from entering the windows of the house during the warmer months, yet light warm sunlight reach the windows in the colder months when the trees lost their leaves.” In the example, the student strategically looked at the functions of tree placement before settling on a design.

4.6.5 Conduct Experiments Confounded vs. Valid Tests & Experiments

Beginners do few to no testing while informed designers run multiple experiments to test their ideas.

- Hypothetical counter-example of beginner designer: “We ran the simulation and it worked so we kept the design.” In the example, the student did not conduct multiple tests to examine different ideas.
- Example of informed designer: “I reconfigured the solar panels angle and placement on the house many times. I tested several different angles for the roof on the side with solar panels to determine which angle generated the most energy, then moved the panels around on the properly angled roof to maximize the energy generation.” In the example, the student tested multiple roof angles in order to determine the best solution for maximizing energy generation.

4.6.6 Revise/Iterate Haphazard or Linear vs. Managed & Iterative Designing

Beginners design in a linear order with no systematic iterative design revision as done by informed designers.

- Hypothetical counter-example of beginner designer: "The design looked good and met the requirements so we did not do any testing." In the example, the student did not revisit any other stages of the design process and proceeded in a linear fashion.
- Example of informed designer: "I used several tests in differing configurations of the energy generated by the solar panels, as well as the energy usage with the house at different angles." In the example, the student highlighted the presence of multiple configurations of solar panels and orientation of the house in his/her design process that helped him/her revise the design.

4.6.7 Reflect on Process Tactic vs. Reflective Design Thinking

Beginners design with little self-monitoring and only reflect after completing the task unlike informed designers who reflect during as well as after the design process. Since think-aloud responses from the students will not be available for analysis, I used the reflection responses to make interpretations about this strategy.

- Example of beginner designer: "I dont think I would really change what I did. As a whole project I could've looked more into how the area effects house energy." In the example, the student did not critically think about how the design could be better.

- Example of informed designer: “If I could do the task over, I would try to challenge myself and create a larger house since my house was at the minimum area. I would also try to incorporate more windows and less solar panels so that my house would be cheaper and it would increase the curb appeal of the house. Adding more windows could also increase the amount of energy generated by the house which would then make the house even more energy efficient.” In the example, the student monitored himself while reflecting on an alternative design idea. S/he reflected on the pros and cons of the design idea and conducts an in-depth analysis of his/her proposed idea.

4.6.8 Code Scheme

For section 2, reflection #1 and #2 were refined over multiple iterations using an adapted version of Crismond and Adams framework to analyze these two sets of reflections. This framework was developed by using Crismond and Adams framework as a starting point followed by iterative refinement using content analysis approach. Based on my content analysis, two new expertise levels have been added to the existing framework. In this adapted framework, I focused only on those design strategies that were visible in my data set by virtue of classroom instructions. A summary of the coding scheme can be found in table 4.5.1

Table 4.2: Summary of Coding Scheme (Part 1)

Design Strategies	Beginning	Adept Beginner	Informed	Adept Informed
Understand the Challenge	Prematurely attempt to solve without identifying key components in problem structure.	Consider possibility of ambiguity in the problem, but make no active attempt to identify and document critical criteria. Consider at least one critical criteria/task.	Identified a few critical criteria and constraints as well as the ultimate goal of the design task.	Identify and describe in depth (several) possible criteria and constraints and relate them to the ultimate goal of the design task. Or references weighted decision matrix.
Build Knowledge	Skip all research and begin solving.	Conduct minimal research before continuing the problem solving process. (i.e. one function from Energy3d)	Evidence of using several given tools such as Energy3D features, course rubrics, etc to learn about the problem, how the system works, relevant cases, and prior solutions.	Combination of several investigations and research outside of the given materials (in addition to Energy3D, or rubrics, etc) to learn about the problem, how the system works, relevant cases, and prior solutions. Example: government site, other research.

Table 4.3: Summary of Coding Scheme (Part 2)

Design Strategies	Beginning	Adept Beginner	Informed	Adept Informed
Weigh Options and Make Decisions	Criteria and constraints are not considered for decision making.	Criteria and constraints are acknowledged, but benefits and trade-offs are not discussed.	Use the trade-offs and potential benefits as the main input parameters of the decision making process.	In depth trade off analysis is displayed along with a clear understanding of the draw backs and benefits of decisions. Clearly recognizing that the refined design is still not a perfect design. Or references weighted decision matrix.
Reflect on Process	Conduct no reflection and dont monitor activities to their plans or proposed solutions.	Conduct little reflection (one criteria mentioned) but do not take into account previous experiences or new information obtained.	Conduct informed reflections based on previous experiences and iterations. Mention more than one criteria.	Recognizes that current design can be optimal, but still imperfect, and therefore room for improvement. Actively and extensively conduct critical thinking practices and directly apply those results towards optimizing their design upon the next iteration.

4.6.9 Understanding the Challenge

There are four distinct patterns of design behavior found within the strategy of Understanding the Challenge. The following are descriptions with examples of these patterns.

- Beginner: Prematurely attempt to solve without identifying key components in problem structure. Example: "I worked on finding a way to lower the energy usage my model house was using for heating during the winter."
- Adept Beginner: Consider at least one critical criteria or possibility of ambiguity in the problem, but make no active attempt to identify and document critical criteria. Example: "Since the activity is individual, I was involved from the beginning till the end in which I had to design a house, decide on different materials, adjust the size and height based on instruction given, put solar panels and sensor and make sure that the building consumes no net energy over a year."
- Informed: Identified most critical criteria and constraints as well as the ultimate goal of the design task. Example: "We first gathered all the individual 3D models and revised each others to get the best model possible, saving the most energy and create the most efficient model. Our best model of three models we got was the most simple in a rectangular shape of walls, net energy being below -800."
- Adept Informed: Identify and describe many possible criteria and constraints and relate them to the ultimate goal of the design task. Example: "I designed a house that was particularly appealing and

comfortable, a design to be later combines with other ideas to get the final solution."

4.6.10 Build Knowledge

There are four distinct patterns of design behavior found within the strategy of Building Knowledge. The following are descriptions with examples of these patterns.

- Beginner: Skip all research and begin solving. Example: " I didnt really use any outside sources when building this solution, excluding the information I learned when completing the Pre-Quiz for this activity. I simply worked with the program enough so that I would know how certain changes would affect the energy efficiency of the home."
- Adept Beginner: Conduct minimal research or investigate one design parameter before continuing the problem solving process. Example: "I read the (anonymized) user manual and they commented about the uses of trees in the program, so I applied it to my houses situation as well."
- Informed: Do multiple investigations and research to learn about the problem, how the system works, relevant cases, and prior solutions. Example: "I used several tests in differing configurations of the energy generated by the solar panels, as well as the energy usage with the house at different angles."
- Adept Informed: Identify and describe many pieces of information in detail and relate them to the ultimate goals in the design task.

Example: “I gathered most of the information from the internet to increase my understanding in zero net energy buildings. I learnt a lot about differents material and the impacts they give and I found several suitable zero net energy building that I could refer to such as Zero- energy test building in Talinn, Estonia”

4.6.11 Weigh Options and Make Decisions

There are four distinct patterns of design behavior found within the strategy of Weighing Options and Making Decisions. The following are descriptions with examples of these patterns.

- Beginner: Criteria and constraints are not considered for decision making. Example: “I decided to have two “must have” criteria because I felt this family needed both. They specifically were asking for a zero-efficiency house, but comfort is a given necessity and if they did not feel comfortable in their home, why would they live there. There were no trade-offs as we could rank the criteria how we pleased and we could have had all of them be must haves or none.”
- Adept Beginner: Criteria and constraints are acknowledged, but benefits and tradeoffs are not discussed. Example: “To decrease the size of the windows to delegate more funds towards solar panels. The windows do not have the most aesthetic appeal.”
- Informed: Use the trade-offs and potential benefits as the main input parameters of the decision making process. Example: “While working on the task, I needed to decide how the home would look, both for curb appeal and for practical reasons. The decision that I

made to go for a more practical home that would allow for lower annual net energy caused a lower amount of curb appeal."

- Adept Informed: In depth trade off analysis is displayed along with a clear understanding of the drawbacks and benefits of decisions. Clearly recognizing that the refined design is still not a perfect design. Example: "After I ran my initial energy analysis, I found out that my house model was inefficient since a large amount of heat was escaping through the windows in the house. I decided to change the window style from single-pane to triple-pane to lower the U factor of the windows. I assumed that if I used triple-pane windows with a lower U factor, the windows would be more insulated and more resistant to heat loss."

4.6.12 Reflect on Process

There are four distinct patterns of design behavior found within the strategy of Reflecting on the Process. The following are descriptions with examples of these patterns.

- Beginner: Conduct little or no reflection and monitoring activities to their plans or proposed solutions. Example: "I would not change anything. I am pleased with my house."
- Adept Beginner: Conduct little reflection but do not take into account previous experiences or new information obtained. Example: "I could make the house more appealing, while keeping its zero energy usage."

- Informed: Conduct informed reflections based on previous experiences and iterations. Example: "If I were to do this activity again, and I had more time to complete the activity, I would try to make a different house for different climate zones and compare the maximum efficiency that I could achieve in each climate zone. In addition, if I were to do this particular task over again, I would try to increase the simplicity of the house without losing energy efficiency by using the same materials for all of the walls of the house."
- Adept Informed: Recognizes that current design can be optimal but still imperfect, and therefore room for improvement. Actively and extensively conduct critical thinking practices and directly apply those results towards optimizing their design upon the next iteration. Example: "If I could the task over, I would definitely take some more time doing my reading and research on zero energy buildings first, before starting my design. This is because there are a lot more resources and information that need to be taken into account in building the house. Apart from that, I would definitely design a better-looking house that cost lesser than what I have designed now. The house would of course be a zero energy building and is eco-friendly one."

4.7 Quantifying Results and Comparing Them

The sample size of 90 students contained 180 reflection reports. These reports were coded from Dataset 2 (90 reports came from reflection #1 and 90 reports came from reflection #2). The next step consisted of quantifying those responses. This process consisted of counting frequencies of each of the strategies according to their level, separately for reflection #1 and #2. Graphing techniques were used to visualize the data. The next step consisted on performing a statistical analysis to identify the effect of students interaction with Energy3D resulted in any changes in their design thinking strategies.

4.8 Chapter Summary

This chapter summarized my methods as well as the new coding scheme. This chapter described the refined coding scheme to show four distinct patterns within the design strategies, and also listed examples.

CHAPTER 5. RESULTS

5.1 Introduction

The purpose of this chapter is to discuss the results of the study.

5.2 Results

The data was analyzed as a pre-post test using a non-parametric Wilcoxon signed rank test. The results from Reflection 2 are not independent of the results from Reflection 1, and I did not assume normal distribution. I compared proportions using paired-data using more than two categories. These categories were considered as ordinal. For these reasons a non-parametric Wilcoxon signed rank test was used.

Table 5.1: Statistical Results for Non Parametric Wilcoxon Signed Rank Test

Strategy	Reflection 1 Mean (SD)	Reflection 2 Mean (SD)	V	r	Z	df	P-value *significant
Understand	2.122 (0.946)	2.956 (1.208)	393.5	0.528	5.007	69	< 0.001*
Weigh	2.856 (0.696)	2.878 (1.090)	1150.0	0.058	0.550	68	0.582
Build	1.978 (0.924)	2.656 (0.996)	328.5	0.515	4.882	62	< 0.001*
Reflect	2.711 (0.927)	2.578 (1.01)	915.5	-0.097	-0.917	56	0.367

Figure 5.1 and Figure 5.2 visually depict the data. Both charts show the evidence of design strategies that are broken down into beginner, adept beginner, informed, and adept informed. Results suggest that before engaging in the design challenge with Energy 3D the most frequent characteristic was Weigh with 48 counts of evidence of informed design patterns. The least frequent strategy identified was also Weigh (1), with a single count in the beginner designer pattern. After students engaged with the design challenge the strategy that showed the most frequent instances was Build Knowledge (38), with the highest count of patterns displayed in the adept beginner level. The least frequent strategy was Build Knowledge (9) with the counts in the beginner level. There seems to be a general shift from beginner/adept beginners to informed/adept informed except for Reflect which does not show a huge shift between R1 and R2.

As shown in Figure 5.3 regarding Understanding the Design Challenge, there was a shift towards more adept informed evidence counts in Reflection 2. There was a large shift from 9 counts of evidence displaying adept informed patterns to 45 counts of evidence displaying adept informed patterns. A Wilcoxon Signed Rank Test revealed a statistically significant change in evidence of more proficient design practices in the reflection 2 results, $z = 5.007$, $p < 0.001$, with an effect size of $r = 0.528$.

For Weighing Options and Make Decisions, there was also an interesting decrease in Informed design patterns, from 48 in reflection 1 to 22 in reflection 2, as shown in Figure 5.4. There was an increase in evidence of adept informed design practices, from 15 in reflection 1 to 35 in reflection 2. A Wilcoxon Signed-Ranks Test indicated that evidence of

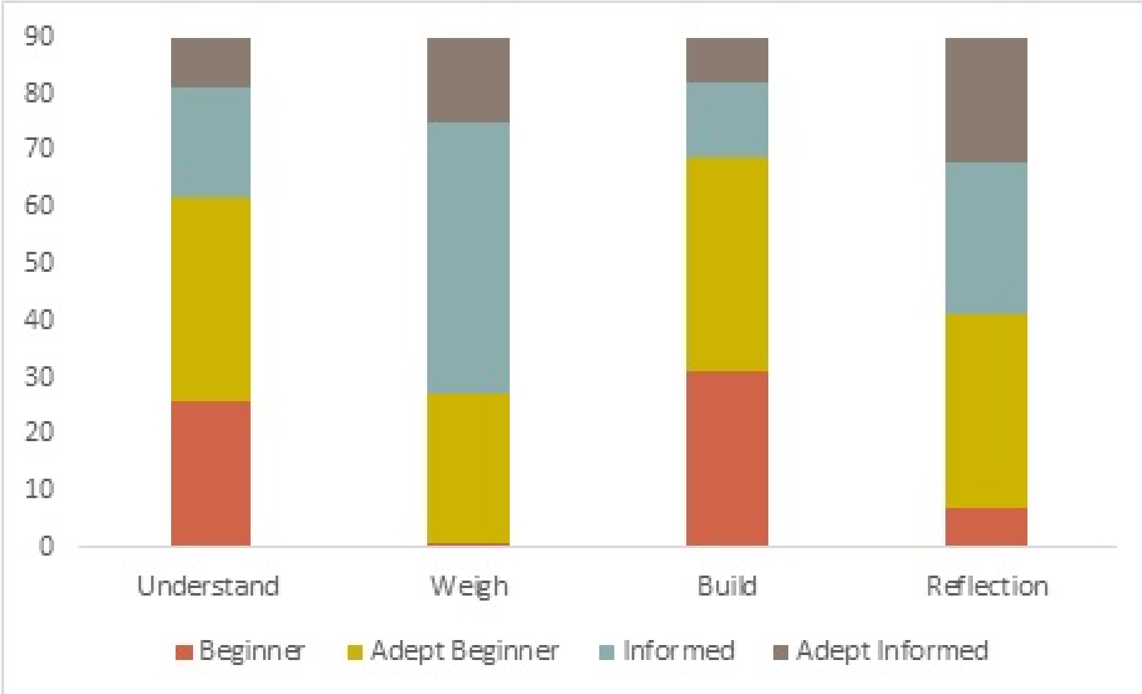


Figure 5.1.: Distribution of expertise level across different design strategies before team work using CAD software

more proficient design practices in reflection 2 was not statistically significantly higher than reflection 1 with $p > 0.001$. A Wilcoxon Signed Rank Test did not reveal a statistically significant change in evidence of more proficient design practices in the reflection 2 results, $z = 0.550$, $p = 0.582$, with an effect size of $r = 0.058$.

In Build Knowledge there was a decrease in beginner counts from 31 in reflection 1 to 9 in reflection 2, and an increase in adept informed counts, as shown in Figure 5.5. There were equal counts of evidence for adept beginner, 38 for both reflection 1 and 2. There was a slight increase in Informed from 13 in reflection 1 to 18 in reflection 2. There was a slightly larger increase in Adept Informed counts from 8 in reflection 1 to 25 in reflection 2. A Wilcoxon Signed Rank Test revealed a statistically

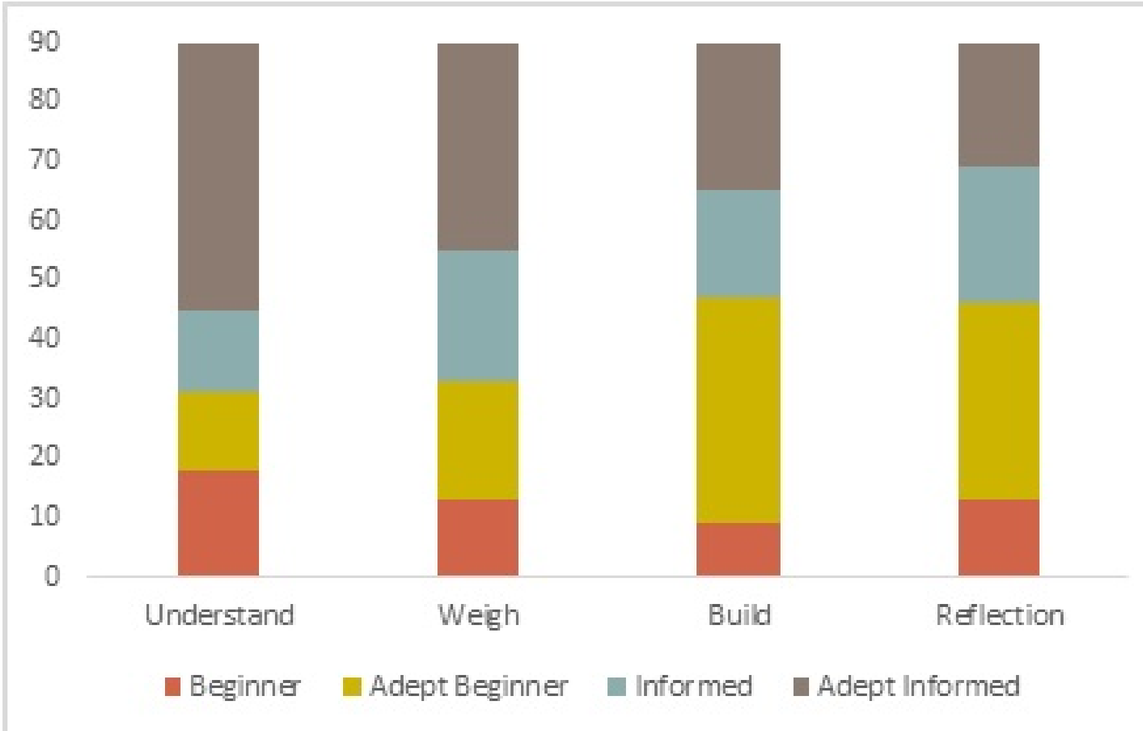


Figure 5.2.: Distribution of expertise level across different design strategies after working in teams using CAD software

significant change in evidence of more proficient design practices in the reflection 2 results, z = 4.882, $p < 0.001$, with an effect size of r = 0.515.

An interesting result occurred in Reflect on Progress, there was very little difference in Reflection 1 and Reflection 2. There was an interesting occurrence in Reflect on Progress in that Adept Beginner, Informed, and Adept Informed all showed a slight decrease in proficient design practice evidence, as shown in Figure 5.6. Evidence of Beginner practices were 7 in reflection 1 and 13 in reflection 2. In Adept Beginner, reflection 1 had 34 counts and reflection 2 had 33 counts. Informed had 27 counts in reflection 1 and 23 counts in reflection 2. Adept Informed had 22 counts in reflection 1 and 21 counts in reflection 2. A Wilcoxon

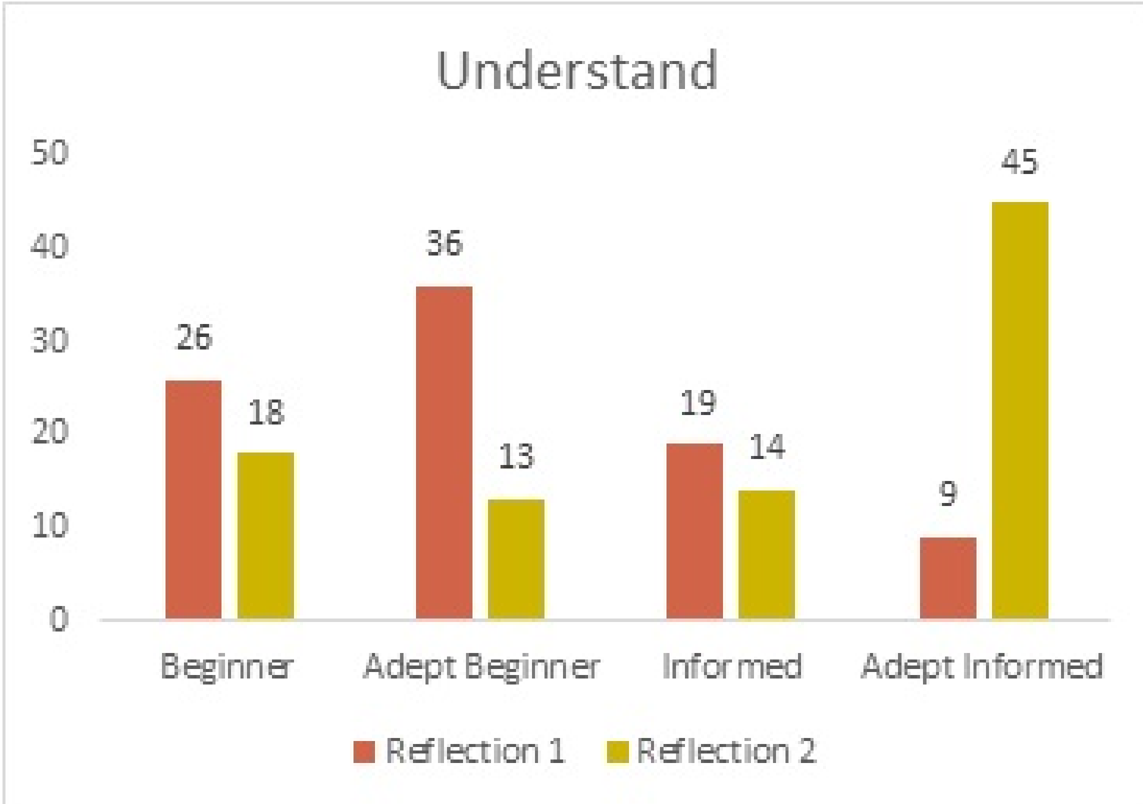


Figure 5.3.: Understand Challenge Change in Reflection 1 and Reflection 2

Signed Rank Test did not reveal a statistically significant change in evidence of more proficient design practices in the reflection 2 results, $z = -0.917$, $p = 0.367$, with an effect size of $r = -0.097$.

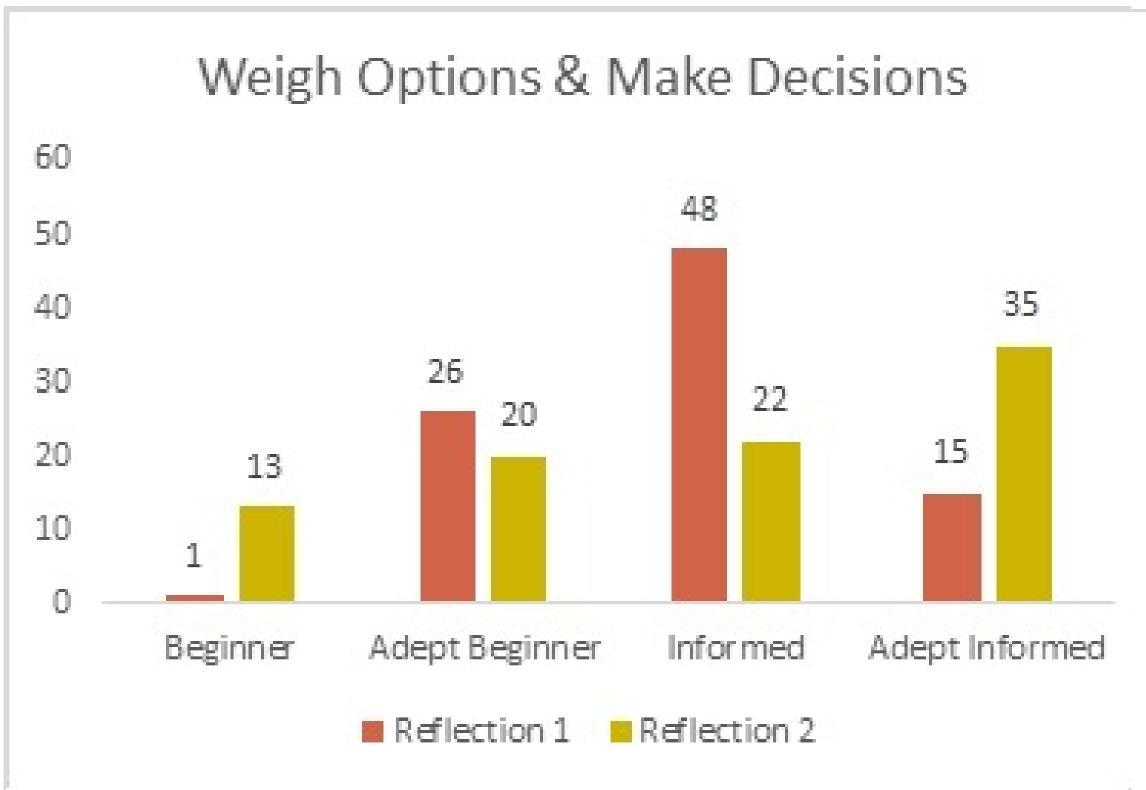


Figure 5.4.: Weigh Options & Make Decisions Change in Reflection 1 and Reflection 2

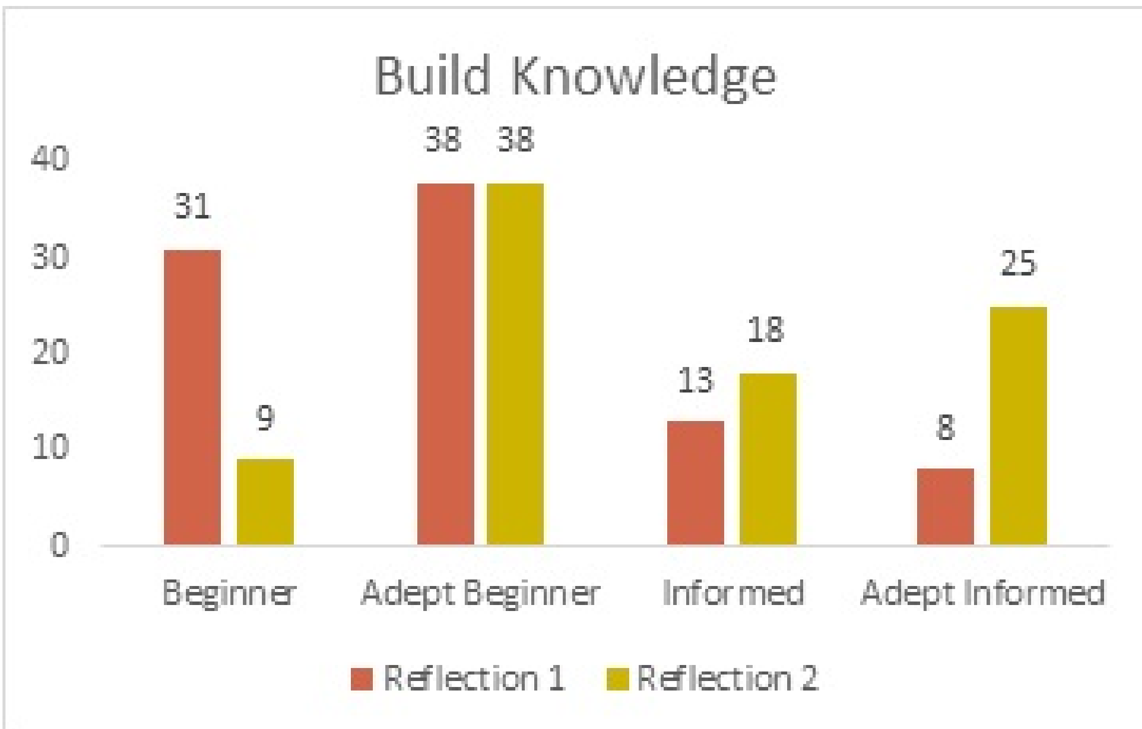


Figure 5.5.: Build Knowledge Change in Reflection 1 and Reflection 2

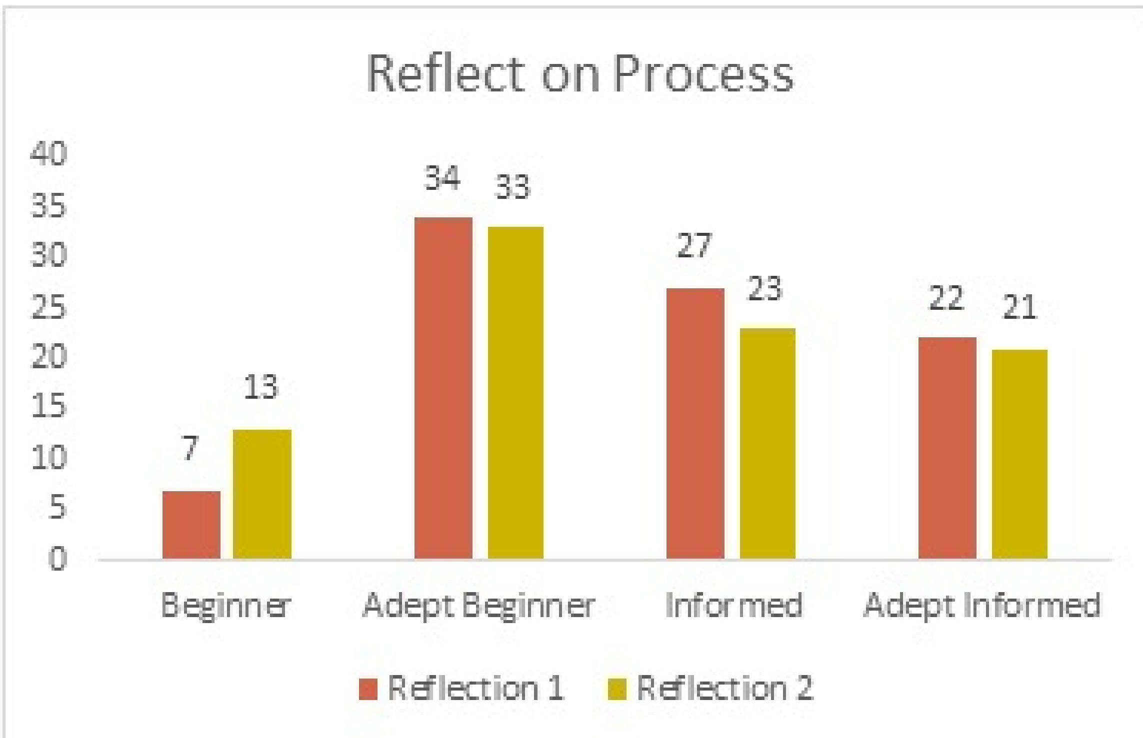


Figure 5.6.: Reflect on Process Change in Reflection 1 and Reflection 2

CHAPTER 6. DISCUSSION

This research study set out to answer questions: 1) To what extent do students demonstrate evidence of design thinking in their reflections? 2) How does design thinking change after a hands-on iterative design learning experience? At this time, it would seem that students demonstrated several different patterns found within the Crismond and Adams Framework, however in only two strategies (Understand and Build) did students show a significant change in the evidence of a shift towards proficient design thinking patterns. In strategies such as Weigh and Reflect, students evidence did not display any significant shift.

6.1 Understanding the Challenge

There was a significant shift towards proficient design thinking practices regarding Understanding the Challenge. One possible reason for the results in Understand the Challenge is that previous work with the CAD after completing Reflection 1 aided the students in understanding the problem. A large effect size of 0.528 indicates that there was a significant change. The collaboration within teams as opposed to individual work could have influenced the evidence of design thinking patterns in their artifacts. When students are first starting to get to know the software in reflection 1, they are working individually. After students work with the software, they form small teams to come up with a final design. Through their collaborative learning, students exchanged information with each other to discuss and compare their interpretation of the problem statement and ultimate goals of the design task.

6.2 Weigh Options and Make Decisions

Regarding Weigh Options and Make Decisions, one of the reasons for the results could be that after students turned in R1 the students participated in an activity that directly addressed benefits and trade-offs. R2 was done after the learning activity and after students had collaborated in a group to discuss their final design. An interesting point is that there was also a small increase in beginner evidence counts. One reason might be that students felt quite confident in their final design and did not consider any design decisions to have any negative trade-offs.

6.3 Build Knowledge

For Build Knowledge results, one reason for this could be that in when Reflection 1 was completed, the students were just starting to explore the project goals and design parameters. In Reflection 2 the students came together as a group and were able to pool their different resources of information, including their research conducted outside of the course materials. A large effect size of $r=0.515$ indicates that there was a significant change. Another interesting point is a key feature of the Energy3D tool itself; the software constantly built knowledge and information as an integral part of the simulation process. This software did not prompt the students to consider trade-offs or reflect.

6.4 Reflect on Process

There was not a large improvement of evidence of design proficiency for this strategy among the students. One interesting thing to note is that several responses in Reflection 2 mentioned they were satisfied with their results and some students mentioned "grades" as being a factor in their complacency. When asked what they would do differently, one student wrote, "Try to design a house which can get full grades in our weighted decision matrix." Other students took a more open ended approach such as encouraging their peers to speak up more or choosing a program that wouldnt crash so much. A few students mentioned trying to get a better grade if they had to do the assignment again. Other examples were too broad to be considered a distinct design pattern such as, "I would try to start off with the best house I could possibly imagine and work my way downwards to the house that I want with given parameters." While these comments provide interesting insight, they do not pertain to the design of the house so they were categorized as "beginner" counts. A suggestion for future work in this design activity would be to specifically ask students to refrain from mentioning anything outside of the direct design activity.

6.5 Implications for Teaching

The results from this study show that interacting with Energy3D CAD simulations for tackling a design task have shown to improve student understanding of the design challenge as well as gathering data to build knowledge about the problem. Methods for teaching engineering design vary as much as the design processes do; there is no single correct method for teaching engineering design (Borgford-Parnell, Deibel, & Atman, 2010). There is a large amount of research that has focused on the task of instilling proficient design practices in the classroom(Dym, Agogino, Eris, Frey, & Leifer, 2005). The Energy3D CAD tool combined with a design thinking learning module is an effective way to teach about real world green energy practices and also experience design thinking practices. “Learning by doing” is emphasized to promote the grasp of scientific concepts as well as the practice of proficient design techniques (Adams, Turns, & Atman, 2003)(Crismond & Adams, 2012)(Lawson & Dorst, 2009) (Schön, 1983). During these design thinking activities, is important to emphasize trade-off analysis during these learning experiences. “Reasoning through benefits and trade-offs of different design alternatives is an important component of decision-making” (Schweingruber, Keller, Quinn, et al., 2012). In a study that also involved Energy3D and design thinking, the results indicated that students did not display evidence of constant iterative analyzation of trade off analysis, but “macro iterations” (Purzer, Goldstein, Adams, Xie, & Nourian, 2015). This aligned with my findings, where the final reflection did not capture the student behavior during one of the “macro iterations”. It is very important to in-still the practice of trade-off analysis in students, but it is a challenging task for everyone not only students since this is not an innate mindset to anyone (Scholten & Sherman, 2006) (Papadouris, 2012).

6.6 Implications for Learning

An important thing to reiterate is that in my study, the first reflection was given after individual work and an introduction to the tool, and the second reflection was given after students worked in teams. This sort of collaborative learning "involves individuals as group members, but also involves phenomena like the negotiation and sharing of meaning that are accomplished interactively in group process" (Bratitsis & Demetriadis, 2013). This sort of research collaboration helps students with efficacy in building scientific knowledge (Stump, Hilpert, Husman, Chung, & Kim, 2011) (Hsiung, 2012). This aligned with the finding that students displayed significant improvement in evidence of proficient building of knowledge in reflection 2 as opposed to reflection 1. This makes sense because the format of the design task in Energy3D provided an environment that promoted collaboration. Collaboration in a learning environment has been linked to "active learning, student-centered learning, problem-based learning, and project-based learning" (Gol & Nafalski, 2007). Design problem that emulate real world contexts often involve social processes (Atman & Nair, 1996) (Atman, Deibel, Borgford-Parnell, et al., 2009) most teams are interdisciplinary which help bring together different viewpoints when tackling ill-defined problems (Kilgore, Atman, Yasuhara, Barker, & Morozov, 2007). It is important to study how students learn design techniques, because the design process is a core aspect of real world engineering (Borgford-Parnell et al., 2010). Design in the real world is messy with very few scaffolds to solve ill-defined problems (Goel & Pirolli, 1992) (Jonassen, Strobel, & Lee, 2006). Therefore it is important to investigate the effects of CAD simulation on student design thinking as it contributes to the existing knowledge that examines the relationship between design learning and technology.

CHAPTER 7. CONCLUSION

This study investigated to what extent do students demonstrate evidence of design thinking in their reflections and also how design thinking changed after a hands-on iterative design learning experience. There were two design strategies that showed a significant shift, and two design strategies that did not show a significant shift. Specifically Build Knowledge and Understand the Challenge showed an improvement towards more informed and adept design practices. Weigh Options and Make Decisions as well as Reflect on Process did not show a significant shift.

CHAPTER 8. FUTURE WORK

Further research needs to be done to observe all of the original design strategies presented in the original Crismond and Adams Framework. This research project only included four, the reason being that this study focused on artifacts that were created after the design activity concluded for the day. The original Crismond and Adams Framework was designed as a way to measure evidence of design patterns throughout the process. Possible future work would be to observe the student groups while they are engaging in collaborative learning activities. Technologies exist within the Energy3D software that would allow for further analysis of student interactions with the tool throughout the design process (Xie, Zhang, Nourian, Pallant, & Bailey, 2014). Regarding teaching and learning, while students completed assignments titled "Reflection" they did not display any improved critical thinking between the first and second reflection. Perhaps more specific questions regarding the students designs could be implemented so the students are forced to think critically in order to receive a good grade. More specific questions would keep students from submitting answers that are irrelevant to the design activity. One example, for a question that targeted critical thinking and what students would do differently next time, students wrote about encouraging their peers to speak up more or choosing a program that wouldnt crash so much. A few students mentioned trying to get a better grade if they had to do the assignment again. Other examples were too broad to be considered as a distinct design pattern, one example being, "I would try to start off with the best house I could possibly imagine and work my way downwards to the house that I want with given parameters." While these comments provide interesting insight, they do not pertain to the design of the house so they were categorized as "beginner" counts. A suggestion for future work in this design activity would be to specifically ask students to refrain from mentioning anything outside of the direct design activity.

APPENDICES

Appendix A: Useful Software Features

A.1 Specifications

Edit → **Specifications** allow you to put in some of your building specifications (cost & size).

A.2 Heat Flux

View → **Heat flux** allows you to see heat flux, defined as The amount of heat transferred across a surface of unit area in a unit time. Also known as thermal flux. The larger the arrows, the greater the heat flux (Figure 9.1).

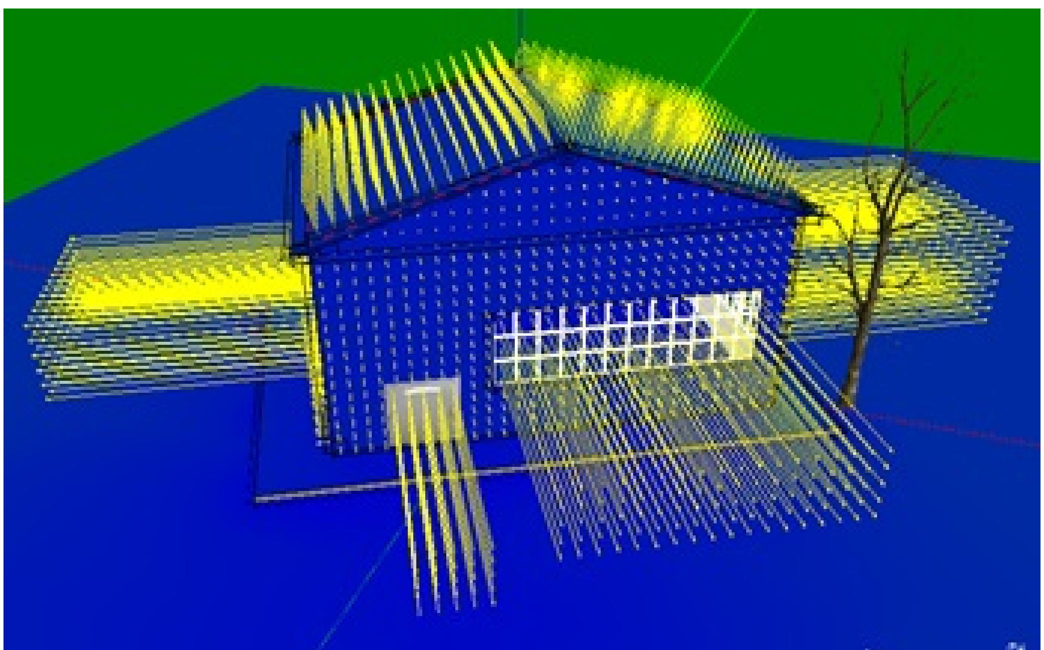


Figure 9.1.: Energy3D Heat Flux

A.3 Heliodon Simulator and Shadow Simulator

Energy3D provides an interactive simulation of the Suns 24-hour trajectory at any given date and latitude. You can observe the Sun path using the Heliodon Simulator as shown in Figure 9.2. If you click the Shadow Button and the Sun Animation Button on the Task Bar, you can you can watch how an object casts shadow on the ground, how the overhang of the roof casts shadow on the walls, and how sunlight shines into the building, as the Sun moves across the sky. Shadow can help you see which side of a building gets more sunlight at a given time. But it can be more useful. For example, this animation can help you decide the positions of the windows. If an Equator-facing window is installed at a higher position, a larger portion of its upper part will be in the shadow of the overhang in the summer, resulting in less solar heating of the building through the window. On the other hand, a higher position of the window allows most sunlight to shine into the building in the winter when the Sun moves at a lower path in the sky.

A.4 Solar Irradiation Simulator

The shadow simulation only shows the solar irradiation at a particular moment in time. It does not capture the effect of the length of the day, which varies from season to season and location to location. A more accurate measure is the daily solar irradiation. The solar energy potential (or solar potential for short) is the total amount of solar energy a building receives from all of its surfaces exposed to sunlight during a period of time, regardless of the energy that may be reflected by the surfaces. In Energy3D, you can evaluate the solar potential of your

Figure 9.2.: Heliodon

building by using the Solar Irradiation Simulator shown in Figure 9.3. The simulator calculates the total solar energy received by the entire building over a day, as well as its distribution over all the surfaces. To show the distribution, each unit area on the ground, a roof, or a wall is drawn in different colors according to the irradiation energy it intercepts. This color distribution is known as a heat map. Typically, blue in a heat map represents low energy and red represents high energy. This solar irradiation heat map is useful because it helps you decide where you should put windows and solar panels.

As the Sun path varies in seasons, the solar potential of a building changes from season to season. The winter and summer situations are of particular interest as the energy demands are the highest in those months. These are the seasons in which solar energy has a larger effect

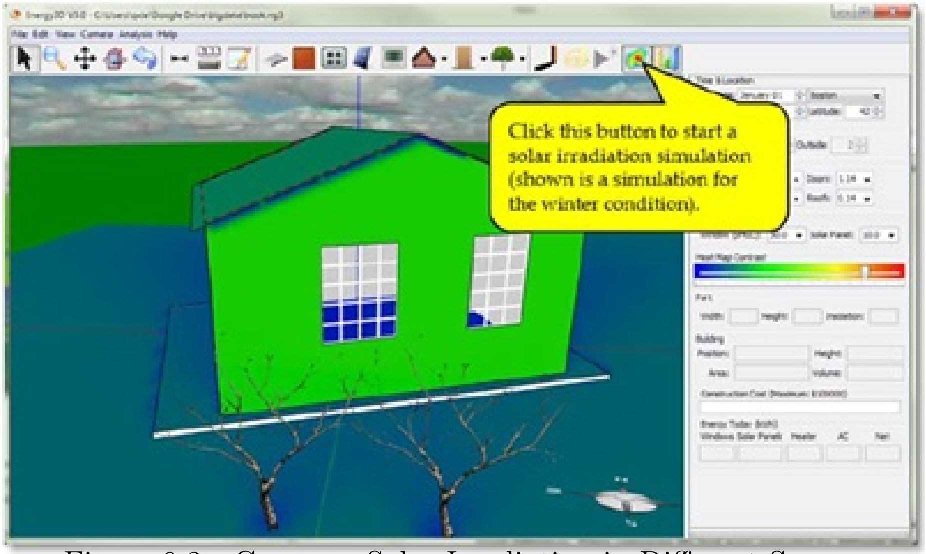


Figure 9.3.: Compare Solar Irradiation in Different Seasons

on the energy efficiency of a building. The Date Spinner Button in the panel on the right side of Energy3D allows you to choose any day of the year. Once you have changed the date, the current heat map goes off and you have to run a new simulation to re-calculate the solar potentials and re-generate the heat map. The Color Scale Slider is for adjusting the color contrast of the heat map to maximize visual differences. When comparing the heat maps generated for different days or locations, do not change the color scale.

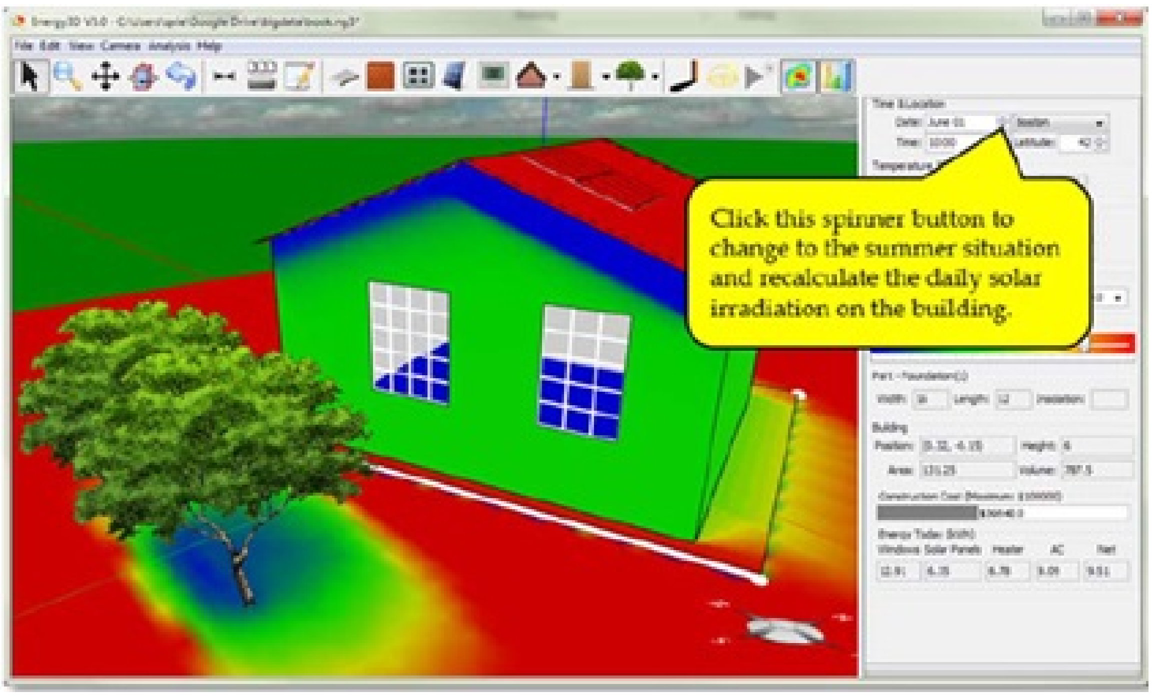


Figure 9.4.: Solar Irradiation

Appendix B: Preliminary Data Analysis

The preliminary analysis of a subset of data from the first class of students analyzed yielded the following tables. It is important to note that the original Crismond and Adams framework indicated that informed designers are constantly reflecting throughout the design process. Since the data is limited to the final artifacts at the end of the design activity, the criteria for beginner vs informed reflective patterns are judged solely on the final artifact statement. Specifically, tables Table 9.1 through Table 9.9 show specific instances of how I am planning to code students responses either as instances of beginner designers or informed designers. Then, proceeded to compare and contrast students overall responses. Table 9.10 presents the preliminary comparison of frequency of instances identified among beginner designers and informed designers. In the final analysis for the second class of students analyzed, I categorized students among beginner designers, adept beginners, informed, and adept informed. I compared the frequency of design patterns before and after the CAD activities and supplemental lectures. Students gained expertise at understanding the design challenge after working in groups on the design challenge and engaged with problem framing while paying attention to the design constraints and design goal. It is likely that the CAD tool afforded students to understand the various variables and their relationship to each other by allowing students to isolate these variables during iterative design. The tool also allowed students to quickly adapt and revise features of the design based upon simulation results or new information gained. This procedure would be much more time consuming if students worked with physical

Table 9.1: Reflection Question 1 (Part 1)

Student ID	Student Response	Beginner vs. Informed
AC 19-11	I tried to minimize the amount of energy used by the four windows that were required in the specifications of the customer.	Beginner (Problem Solving): Student assumed the design task is a well-defined problem.
AK 19-01	I had to create a two-story house that was net-zero energy efficient.	Beginner (Problem Solving): Student assumed the design task is a well-defined problem.
AM 19-26	I reconfigured the solar panels angle and placement on the house many times. I tested several different angles for the roof on the side with solar panels to determine which angle generated the most energy, then moved the panels around on the properly angled roof to maximize the energy generation.	Informed designer (Conduct Experiments, Revise/Iterate): Student states that he/she reconfigured initial design and conducted several tests.
AR 19-22	I placed deciduous trees in such a way that they blocked sunlight from entering the windows of the house during the warmer months, yet light warm sunlight reach the windows in the colder months when the trees lost their leaves.	Informed designer (Balance Benefits &Trade-offs): Student took into account the pros and cons of using trees in two seasons and decided to use deciduous trees because of their unique characteristics.

prototyping materials at this stage instead of a CAD model. The easy-to-use visual feedback (e.g., graphs and heat map) given by the tool may have helped students frame the problem better instead of jumping into problem-solving mode like beginner designers typically do.

Table 9.2: Reflection Question 1 (Part 2)

Student ID	Student Response	Beginner vs. Informed
AS 19-29	I worked to make a zero or negative energy house.	Beginner (Problem Solving): Student viewed task as straightforward and well-defined.
BH 19-23	One main task that I focused on while completing the Energy3D Individual Solution was making sure the structures cost remained under the constraint of $50,000. This was one of the more difficult tasks, as I had to find a way to balance curb appeal with cost and efficiency. This was completed by analyzing the possible placement options for various windows, testing different shapes and sizes, and determining how many different windows should be placed on the house.	Informed designer (Weigh options): Student stated having to balance features of the house with overall cost, efficiency, and curb appeal.
BH 19-28	One specific task was making the house fit the size requirements	Beginner (Problem Solving): Student viewed task as straightforward and well-defined.

Table 9.3: Reflection Questions 2 and 3 (Part 1)

Student ID	Student Response	Beginner vs. Informed
AC 19-11	I concluded that windows in the summer led to too much heat in the house and added trees in front of them, but in the wintertime the windows helped heat the house. I then made the trees deciduous so that the trees could cool off the house in the summer and let the Sun through to heat the house in the winter. The trees added to the cost of the house that I could have used for more solar panels.	Informed designer (Balance Benefits & Trade-offs): Student took into account the pros and cons of incorporating deciduous trees.
AK 19-01	I had to decide on how many windows to place on my house, and where to place them. I also had to decide where to place trees in regard to the windows. I ultimately decided to place majority of the windows on the south side of the house, since that side receives majority of the sunlight. I placed two small windows on each of the other sides of the house, but that was only to meet the requirements of the house. My decision resulted in a beneficial trade off, since not only did the small amount of windows save a lot of money, but it also greatly contributed to the amount of the energy generated by the house. The amount of windows with trees relatively close the windows allows the sunlight to warm the house in the window, but the trees provide shade for the windows in the summer months which ends up cooling the house. My decision does assume however that the weather is always sunny, when this is a big assumption since it is often cloudy and rainy in Chicago which is where the house is located.	Informed designer (Balance Benefits & Trade-offs): Student took into account the pros and cons of the amount of windows versus the temperature of the house.

Table 9.4: Reflection Questions 2 and 3 (Part 2)

Student ID	Student Response	Beginner vs. Informed
AM 19-26	I had to decide whether to maximize the energy saving potential of the house or sacrifice some for aesthetics. I decided in favor of the aesthetics, leading to a slightly larger surface area of the house facing the sun, but a better-looking house. The form versus function debate was the main problem in my case.	Informed designer (Balance Benefits & Trade-offs): Student took into account the pros and cons of aesthetics and energy efficiency.
AR 19-22	I had to decide exactly where to put the deciduous trees. They are required to be at least a certain distance from the house, but their shadows still had to reach the windows when I wanted them to. I had to find a happy medium as far as my tree placement to that they shaded my windows but did not block sunlight from hitting my solar panels.	Informed designer (Balance Benefits & Trade-offs): Student took into account the pros and cons of deciduous trees and their shadow placement blocking the location of a solar panel.
AS 19-29	I decided to use the best materials for the walls to help insulate the building. It cost more to use the more expensive materials.	Informed (Weigh options): Student decided to use the best insulation although it costs more money.

Table 9.5: Reflection Questions 2 and 3 (Part 3)

Student ID	Student Response	Beginner vs. Informed
BH 19-23	One main decision I had to make was deciding the size of each window. Large windows would look nice and add curb appeal, but they would not be beneficial in keeping the energy consumption at zero. Small windows would be consistent with the net-zero energy goal, but would not add any beauty or curb appeal. I had to find a way to ensure that my house had curb appeal and energy efficiency. The main compromise I had to make in my window planning involved window sizes. I decided to compromise by placing a combination of large and small windows on my house to provide the house with the necessary curb appeal but also still meeting the energy requirements.	Informed designer (Weigh options): Student had to balance features of the house with overall cost, efficiency, and curb appeal.
BH 19-28	I decided to go slightly over what the exact requirements were. I assumed that the program was giving me the area of my house and not a different area of some sort.	Beginner (Weigh options): Student did not list a specific trade-offs pros and cons as related to their specific design.

Table 9.6: Reflection Question 4 (Part 1)

Student ID	Student Response	Beginner vs. Informed
AC 19-11	I read the Energy3D user manual and they commented about the uses of trees in the program, so I applied it to my houses situation as well.	Informed designer (Doing Research): Student read instructional material that impacted the final design decision.
AK 19-01	I used the sun heliodon in the design model to help determine which side of the house received the majority of the sunlight. I also used the energy analysis tool for the building to help determine how each change affected the total net energy.	Informed designer (Doing Research): Student used available tools ahead of time to research optimal solutions.
AM 19-26	I used several tests in differing configurations of the energy generated by the solar panels, as well as the energy usage with the house at different angles.	Informed designer (Revise/Iterate): Student tested configurations and revised and iterated the design.
AR 19-22	I researched on the internet what it means for a house to have curb appeal. I then applied some tips I found for increasing curb appeal to my house.	Informed designer (Doing Research): Student used available tools ahead of time to research optimal solutions.
AS 19-29	I used research on u-values to know that lower u-values corresponded with materials that insulated better.	Informed designer (Doing Research): Student used available tools ahead of time to research optimal solutions.

Table 9.7: Reflection Question 4 (Part 2)

Student ID	Student Response	Beginner vs. Informed
BH 19-23	To make this decision, I used the yearly energy analysis tool built in Energy 3D to determine which window arrangement would be the best for my house. I had to make sure that the placement was not detrimental to the net-zero energy goal nor the curb-appeal goal. This was achieved with this compromise.	Informed designer (Doing Research): Student used available tools ahead of time to research optimal solutions.
BH 19-28	I used the area button on the software.	This response does not reflect any design behavior.

Table 9.8: Reflection Question 5 (Part 1)

Student ID	Student Response	Beginner vs. Informed
AC 19-11	I would try to minimize costs on walls by creating a house featuring smaller walls and a pointy roof. The roof would also be able to hold more solar panels that would be available from the lowered cost of walls.	Informed designer (Troubleshooting): Student identified problematic areas such as the costs of walls and proposed an alternative.
AK 19-01	If I could do the task over, I would try to challenge myself and create a larger house since my house was at the minimum area. I would also try to incorporate more windows and less solar panels so that my house would be cheaper and it would increase the curb appeal of the house. Adding more windows could also increase the amount of energy generated by the house which would then make the house even more energy efficient.	Informed designer (Reflective Design Thinking): Student identified a problematic area that upon further evaluation and new information would propose a better solution.
AM 19-26	I would have tried putting function over form next time and seeing just how low of an energy cost I could reach, then incorporate any changes from that into my current house model.	Informed designer (Reflective Design Thinking + Weigh Options): Student made a decision to put aside aesthetic in order to optimize energy efficiency.
AR 19-22	If I could do the task over, I would attempt to make my house look more attractive while still fulfilling the requirements. I could have been more artistic and creative in this area.	Informed designer (Reflective Design Thinking + Weigh options): Student put aesthetics aside to try to optimize energy efficiency.

Table 9.9: Reflection Question 5 (Part 2)

Student ID	Student Response	Beginner vs. Informed
AS 19-29	I would try to spend less by maybe using less solar panels.	Informed designer (Reflective Design Thinking): Student wants to lower cost by using less panels.
BH 19-23	Overall, I could probably try to look for other possible changes to compensate for larger windows. In my solution, I only looked for changes in the windows shapes and placement. I could have looked into solving this problem with strategic tree placement or using solar panels to generate energy to offset the energy loss from the larger windows.	Informed designer (Weigh Options): Student wants to balance solar panels and cost.
BH 19-28	I dont think I would really change what I did. As a whole project I couldve looked more into how the area effects house energy	Beginner (Reflect on Process): Student does little revising or reflecting on past decisions in order to possibly alter the current version of the final design.

Table 9.10: Frequency Count of Data Set 1

Pattern	Beginner	Informed
A. Problem Solving vs. Problem Framing	3	-
B. Skipping vs. Doing Research	1	5
C. Idea Scarcity vs. Idea Fluency	-	-
D. Surface vs. Deep Drawing & Modeling	-	-
E. Ignore vs. Balance Benefits and Trade-offs	1	11
F. Confounded vs. Valid Tests and Experiments	-	1
G. Unfocused vs. Diagnostic Troubleshooting	-	1
H. Haphazard or Linear vs. Managed and Iterative Designing	-	1
I. Tacit vs. Reflective Design Thinking	1	4

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